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# In Search of the 10-Centimeter Range Measurement

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The BepiColombo mission to Mercury desires more accurate radio metric ranging measurements to study relativistic effects on the planet's orbit around the Sun. Ranging measurements as accurate as 10 cm have been proposed for this purpose and will require improvements in spacecraft hardware and calibration of effects from the transmission media. But there are also improvements needed to the Deep Space Network (DSN) ranging system to achieve this goal. Delay through the equipment must be either controlled or calibrated beyond the current 2-m requirement. In 2009, a series of tests was performed to characterize the stability of range delay through the DSN uplink and downlink equipment. It was shown that stability is not consistent with the higher accuracy and that a more advanced calibration technique is needed.

## I. The Deep Space Network Ranging System

The Deep Space Network (DSN) ranging system supports spacecraft navigation and radio science observations. A particularly challenging set of radio science observations has been proposed for the BepiColombo mission that will require 10-cm ranging accuracy, or about a factor of 10 improvement over current performance [1]. The Deep Space Network (DSN) ranging system consists of five main components:

(1) The uplink (UPL) subsystem, which modulates the uplink carrier with ranging tones.

(2) The transmitter (TXR) subsystem, which amplifies the uplink signal.

(3) The antenna subsystem, which focuses the RF energy on both the uplink and downlink.

(4) The low-noise amplifier (LNA) subsystem, which amplifies the received downlink signal.

(5) The downlink tracking and telemetry (DTT) subsystem, which demodulates the ranging tones from the carrier and performs the ranging measurements.

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The ranging system also utilizes a test translator that translates the uplink signal frequency (modulated carrier) to the downlink frequencies, effectively emulating a spacecraft transponder. This capability is used to conduct testing and obtain calibration data, as shown below. A more detailed description of the DSN ranging system and its capabilities can be found in the *DSN Telecommunications Link Design Handbook* [2].

### A. Test Configurations

Two methods of measurement of the DSN tracking station internal range exist: (1) short-loop and (2) long-loop. In short-loop testing, the carrier with ranging modulation output from the UPL passes directly into the test translator. The test translator then translates the signal to the downlink frequency, it is downconverted to IF, and then input to the DTT where ranging measurements are generated.

In the long-loop configuration, the UPL provides the signal to the transmitter. The ranging calibration coupler on the transmitter provides the input to the test translator. Again, the signal is then downconverted to IF and input to the DTT.

Diagrams showing both test configurations are shown in Figure 1.

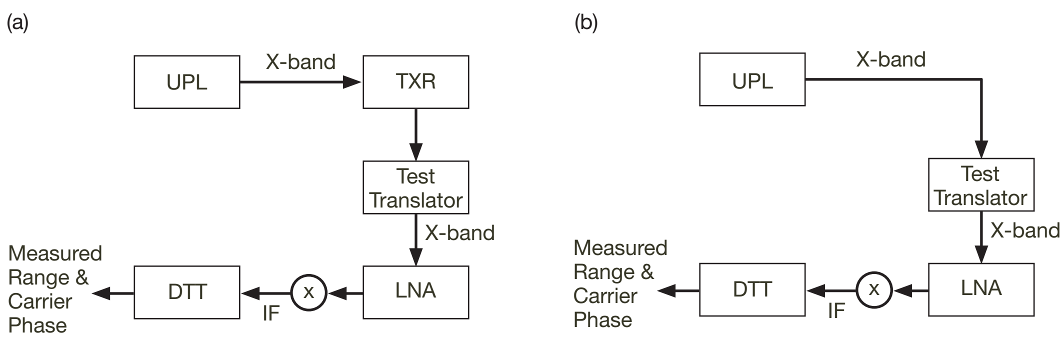


**Figure 1. (a) Long-loop test setup; (b) short-loop test setup.**

In normal ranging operations with a spacecraft, the range delay is measured prepass using the long-loop test configuration. This measurement is called precal or station delay. Delays through the antenna subsystem, called Z-heights, are measured separately and provided to users. The ranging users (e.g., spacecraft navigation or radio science) calibrate the range measurements taken during the tracking pass by removing the station delay and Z-height measurements. It has been assumed that the range delay thus calibrated remains constant throughout the tracking pass.

### B. The Starting Point

The starting point for the study was a measurement of DSN internal range made simultaneously with Cassini spacecraft ranging at DSS-14 made by Dong Shin. The measurements were made by setting the transponder turnaround ratio on the test translator to provide a calibration signal out of the ranging coupler on the transmitter that was shifted in frequency away from the Cassini downlink. A second DTT was used to measure the station delay. A plot of the data is provided in Figure 2.

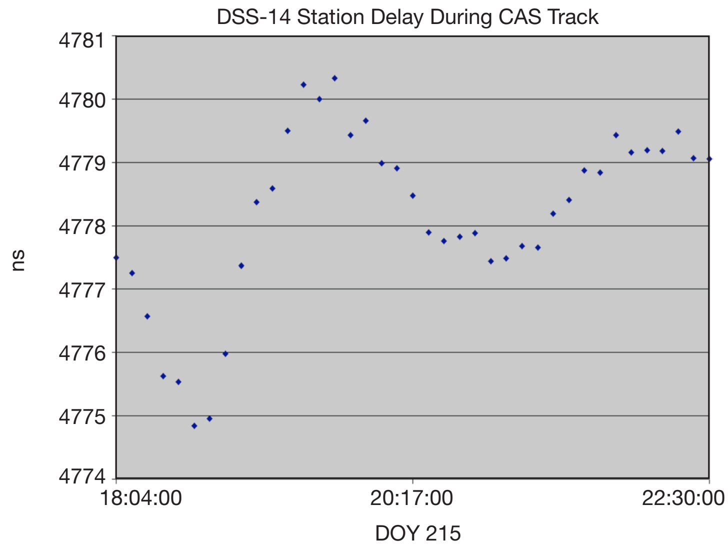


**Figure 2. DSS-14 station delay during the Cassini track.**

Peak-to-peak variations of 5 ns were observed. The subsequent observation program was designed to validate these results and attempt to discover the cause, and propose methods for control or calibration of this varying ranging term.

### C. Approach

Characterizing the internal range delay using X-band uplink/X-band downlink ranging was chosen since the BepiColombo mission will use these links. The observation program proceeded by first establishing the baseline DSN equipment performance. Two facilities were used: (1) the Receiver/Exciter Laboratory in JPL's Building 238, room 527; and (2) the DSN Test Facility (DTF-21). These facilities contain replicas of DSN equipment found at the DSN's Signal Processing Centers (SPCs) and antennas, with the exception of the antenna microwave equipment, including the transmitters. The 238-527 laboratory does not have a fiber-optic run simulating the signal distribution at the Deep Space Communications Complexes (DSCCs), but DTF-21 does. In addition, the 238-527 laboratory is not temperature controlled as stringently as SPC-10, but DTF-21 is temperature controlled to the same specification as SPC-10.

Following the establishment of the equipment baseline, the next step was to characterize the internal range variations at DSS-25. This station was selected because (1) it was specially equipped for superior phase stability; and (2) its beam-waveguide design meant that the transmitter and test translator are in the pedestal so the carrier and ranging signal do not travel through the cabling and waveguide required to reach the feedcone and back, as it would at DSS-14 or DSS-15. The underlying assumption was that DSS-25 should produce the most stable ranging calibration results available at the Goldstone DSCC.

Internal ranging data would be taken at other DSN antennas as opportunities became available for comparison and contrast with the DSS-25 results.

#### D. Laboratory Measurements

The first laboratory results from 238-527 were obtained in December 2008. Ranging from the UPL was passed through the test translator directly to the DTT; there was no LNA or TXR in the test configuration. Static ranging data was acquired for about 30 hours. The results are shown in Figure 3.

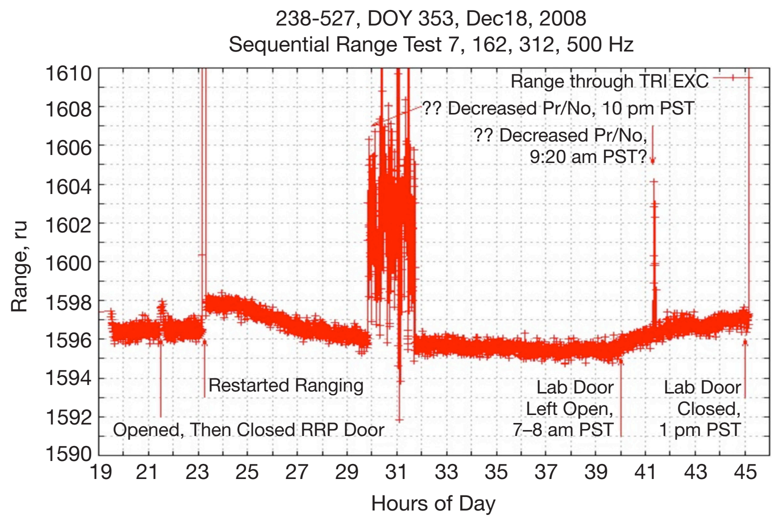


**Figure 3. First laboratory results from 238-527, December 18, 2008.**

These plots show range variation in range units (ru). A range unit and a nanosecond can be seen as equivalent for the purposes of this article. An exact definition of a range unit can be found in [2]. As can be seen, the variations in range can be correlated to events affecting the thermal environment of the equipment. The cause of the anomaly resulting in the loss of receiver lock at about hour 30 is unknown.

The second set of laboratory measurements is also from the 238-527 laboratory. This data set covers almost 160 hours, or almost a week. The results are shown in Figure 4.

Again, variations in the measured range all correlate to events affecting the thermal environment of the equipment. For example, the large, 5 ru increase at about hour 70 correlates with the air conditioner being turned off for servicing. It is estimated that the temperature increased by about 80 deg C (150 deg F), or about 1 ru/deg C.

Finally, results were obtained from a ranging systems performance test (SPT) performed at DTF-21 in April 2009. The test was run over 60+ hours with the equipment in a thermally controlled environment consistent with the environment at SPC-10. The peak-to-peak ranging variation observed was 1.77 ns.

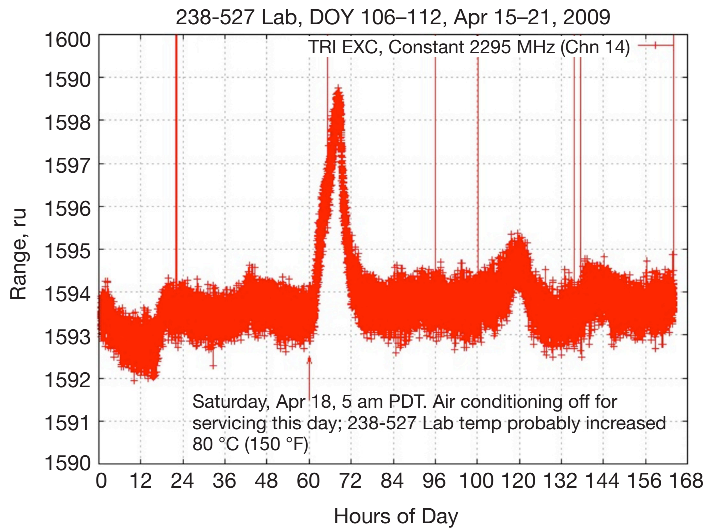


**Figure 4. Second set of laboratory results from 238-527, April 15–21, 2009.**

The conclusion reached from the laboratory testing is that provided an environment with a stable temperature, the internal range of the DSN equipment will produce very stable ranging results.

## II. DSS-25 Results

For the May 13, 2010 test, the long-loop configuration was used, but the IF was also provided to the Radio Science Receiver (RSR). The RSR was configured to digitally record the translated downlink carrier and both the ranging clock tones. This test setup is shown in Figure 5.

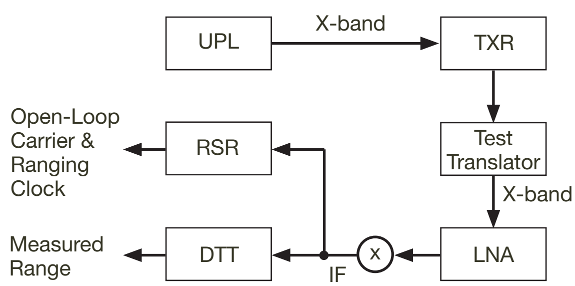


**Figure 5. DSS-25 test setup, May 13, 2010.**

### A. DSS-25 May Tests

On May 13, the test setup that included the RSR was used to collect internal range measurements. The test was repeated without the RSR on May 14 by Bruce Klein. The results from the DTT are shown in Figure 6.

The results from the analysis of the May 13 RSR data by Meeyong Paik and Jim Border are shown in Figures 7, 8, and 9. RSR data collection was performed by Gene Goltz.

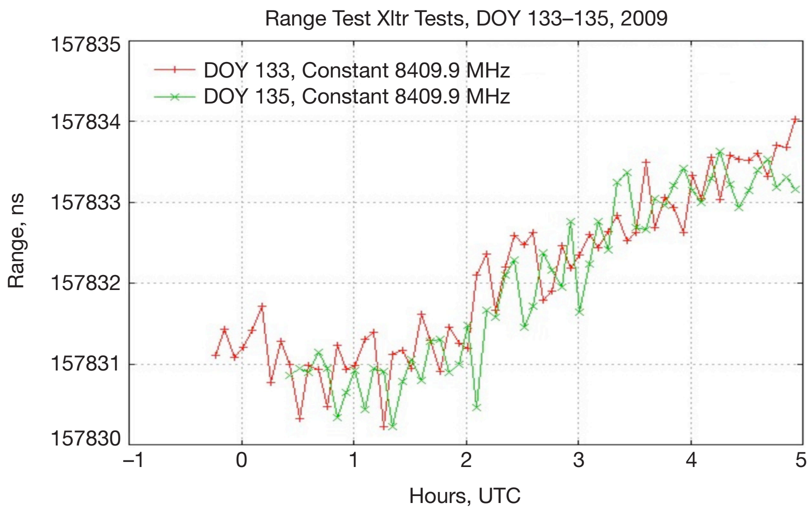


**Figure 6. DSS-25 range tests, DOY 133–135, 2009.**

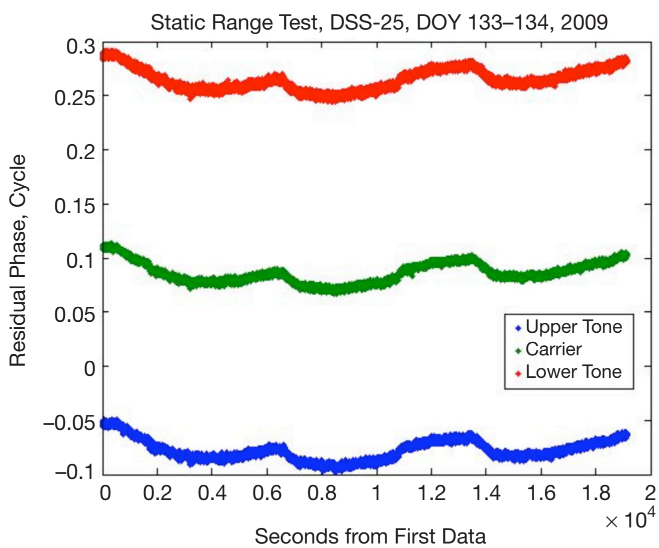


**Figure 7. Static range test, DSS-25, May 13, 2009. The plot shows the residual phase of the carrier and the higher and lower range clock tones.**

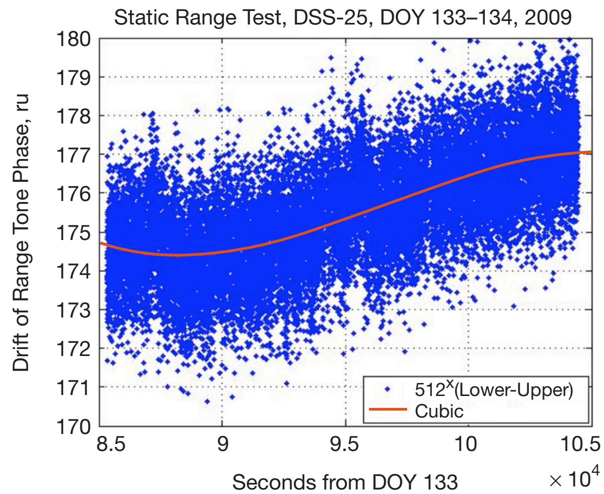


**Figure 8. Static range test, DSS-25, May 13, 2009. The plot shows the range measurement derived from the RSR data.**

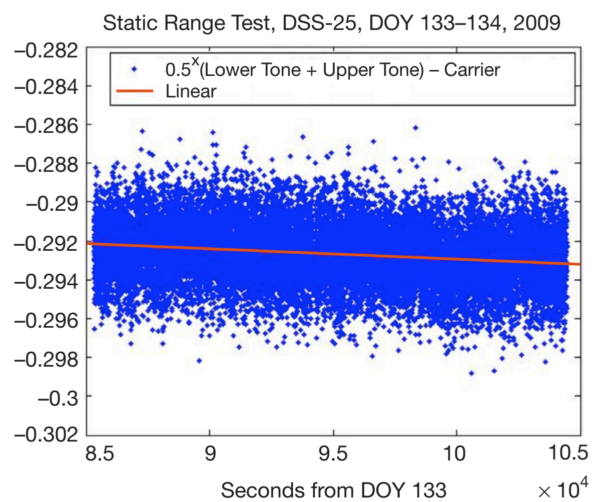


**Figure 9. Static range test, DSS-25, May 13, 2009. The plot shows the frequencies of the higher and lower frequency range tones relative to the carrier.**

**B. Conclusions from the May Tests**

The DTT measurements show the internal range increasing by about 3 ns over a period of 3 hours on both nights. The amount and rate of increase appear consistent on both May 13 and 14.

The measured range by the DTT is consistent with the results of the RSR data analysis: the variation is not due to measurement by the DTT. The carrier phase is also stable throughout the test period. The variation in measured range seems to be caused by the spectral movement of the range tones toward the carrier frequency.

### C. DSS-25 July 2 Test

A short-loop test was conducted by Bruce Klein on July 2. The ranging measurement results and the carrier phase measurement results are shown in Figures 10 and 11.

These results show very stable range measurements and carrier phase in the short-loop configuration spanning the evening hours that produced range variations at DSS-25 in May.

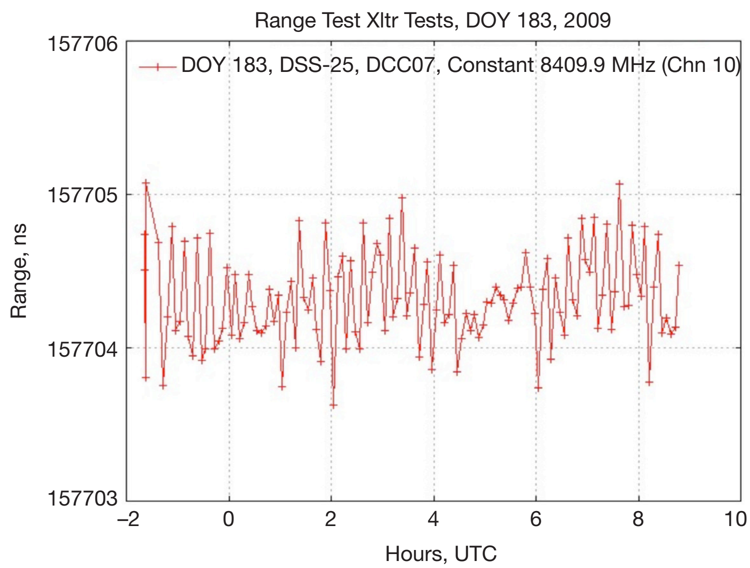


**Figure 10. DSS-25 short-loop test, July 2, 2009: ranging measurement.**

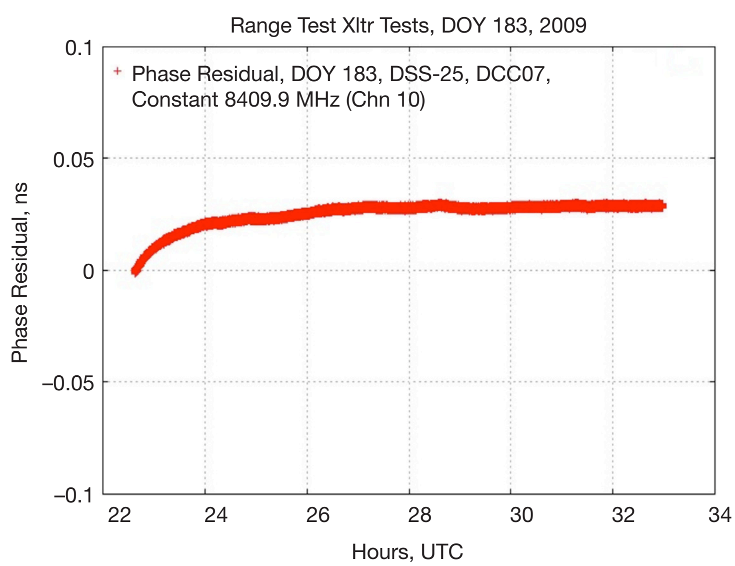


**Figure 11. DSS-25 short-loop test, July 2, 2009: carrier phase measurement.**

### D. DSS-25 August Tests

The results from the May tests and the July 2 test suggested that the range variations may not be the result of any equipment in the short-loop configuration. To test this, three tests were run at DSS-25 on consecutive nights in August — the 27th, 28th, and 29th. Scott Bryant created a command script to switch the ranging configuration from short-loop to long-loop every five minutes. Range measurements were generated every 30 seconds. The results are shown in Figure 12.

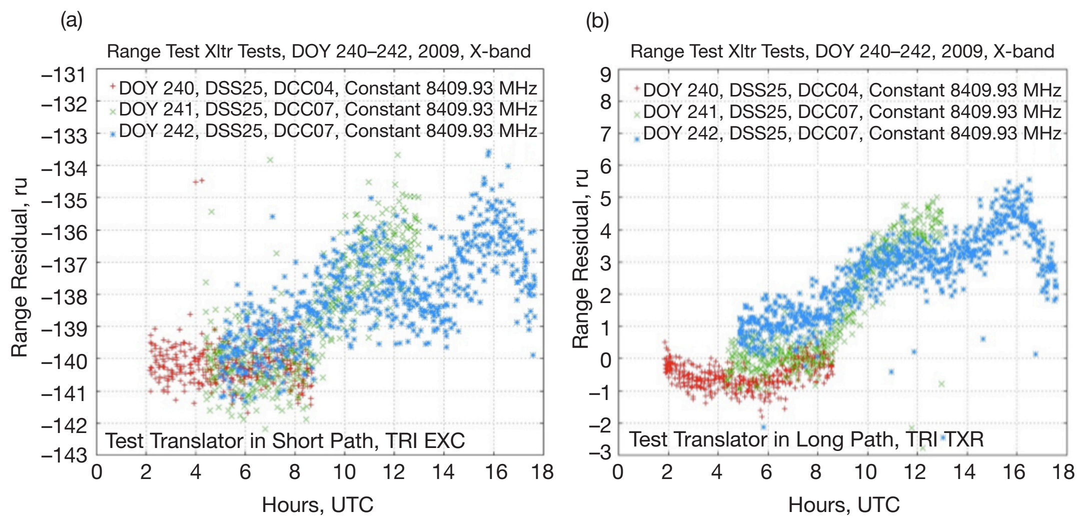


**Figure 12. DSS-25 tests in August 2009: (a) short-loop configuration; (b) long-loop configuration.**

The increase in scatter of the short-loop measurements is due to the poorer signal-to-noise ratio (SNR). The results show that the range variation in the short-loop equipment is roughly equivalent to the variation in the long loop — the opposite of the hypothesis tested. Also surprising is that while the increase in range looks very much like that observed in May, the increase starts about midnight local time, not at sunset as in the tests performed in May. The timing of the increase in range also starts later in the test period than in the May tests. This seems to rule out diurnal effects or “warm-up” issues.

## III. Results from Other Beam-Waveguide Antennas

### A. DSS-24 Test Results

On June 17, a long-loop test was conducted by Bruce Klein. The results are shown in Figure 13. These data taken during midday show good range and carrier stability.

### B. DSS-26 Test Results

Two tests were conducted by Bruce Klein at DSS-26. On May 24, long-loop testing was performed and on July 2, short-loop testing was conducted. The results are shown in Figures 14 and 15. Both tests show good range measurement and carrier phase stability.

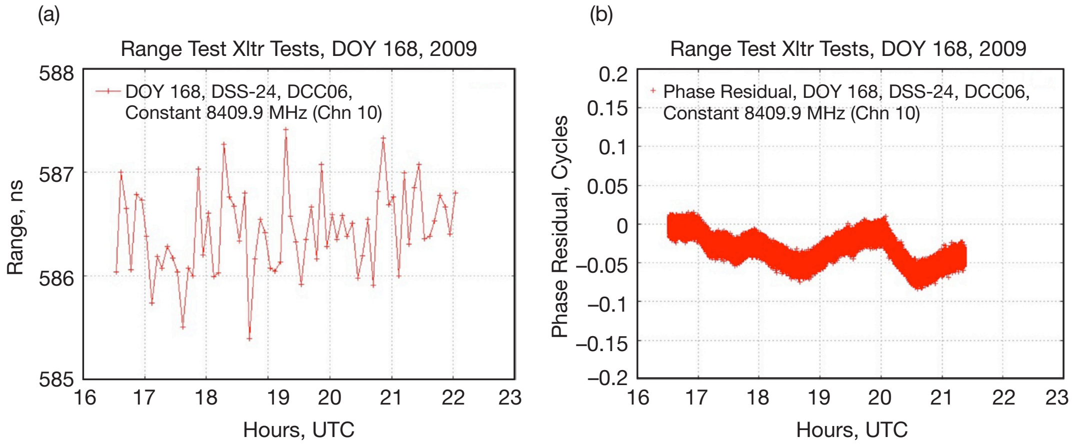


**Figure 13. DSS-24 long-loop test, June 17, 2009: (a) ranging measurement; (b) carrier phase measurement.**

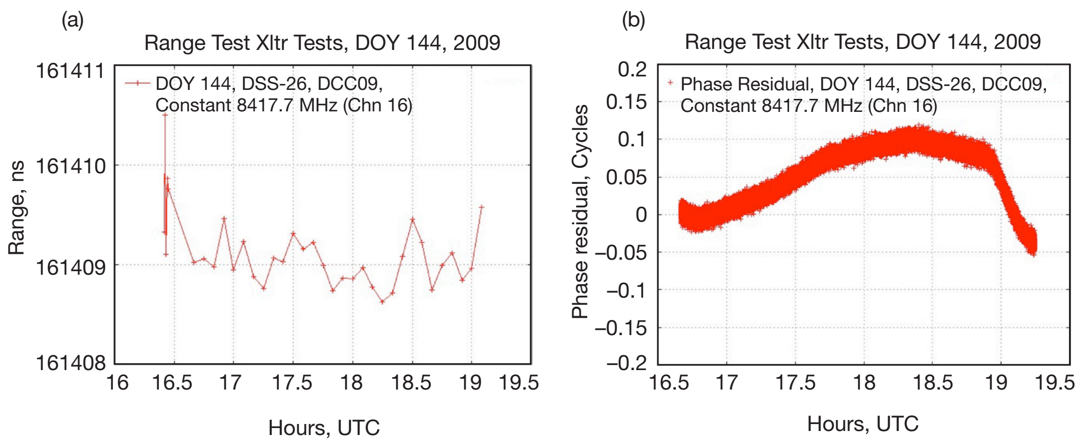


**Figure 14. DSS-26 long-loop test, May 24, 2009: (a) ranging measurement; (b) carrier phase measurement.**

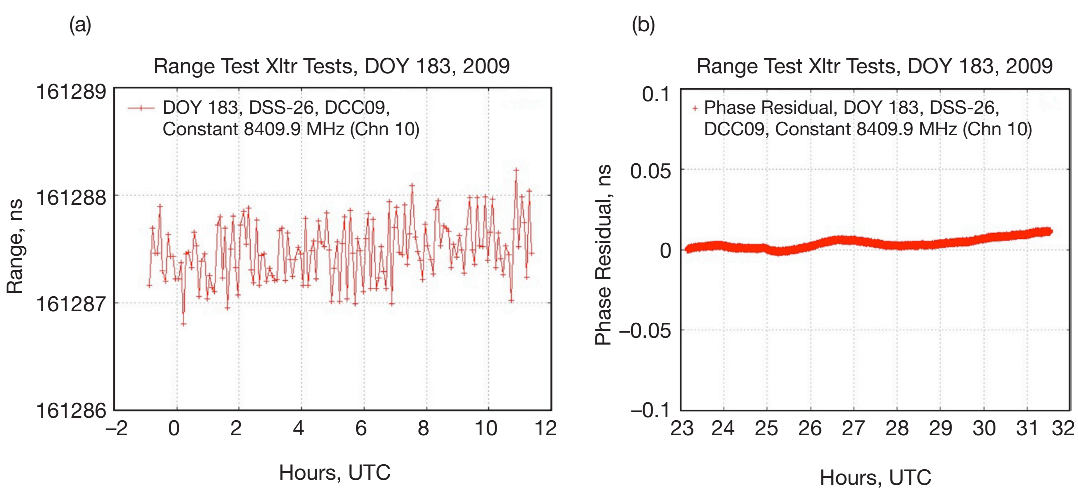


**Figure 15. DSS-26 short-loop test, July 2, 2009: (a) ranging measurement; (b) carrier phase measurement.**

## IV. Non-Beam-Waveguide Antenna Results

Long-loop testing was performed by Bruce Klein at DSS-14 and DSS-15. The DSS-14 test was conducted on June 4 and the DSS-15 test was conducted on May 21 and June 4. The results are shown in Figures 16, 17, and 18.

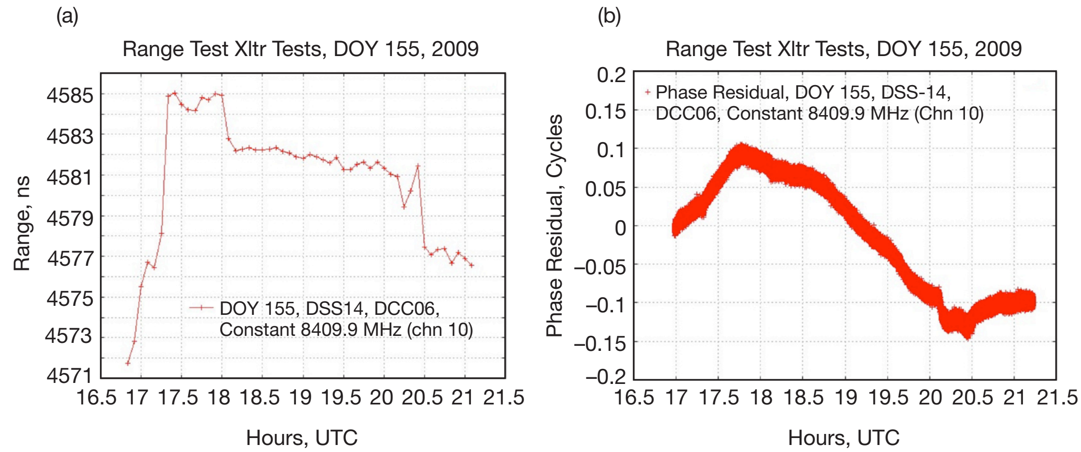


**Figure 16. DSS-14 long-loop test, June 4, 2009: (a) ranging measurement; (b) carrier phase measurement.**

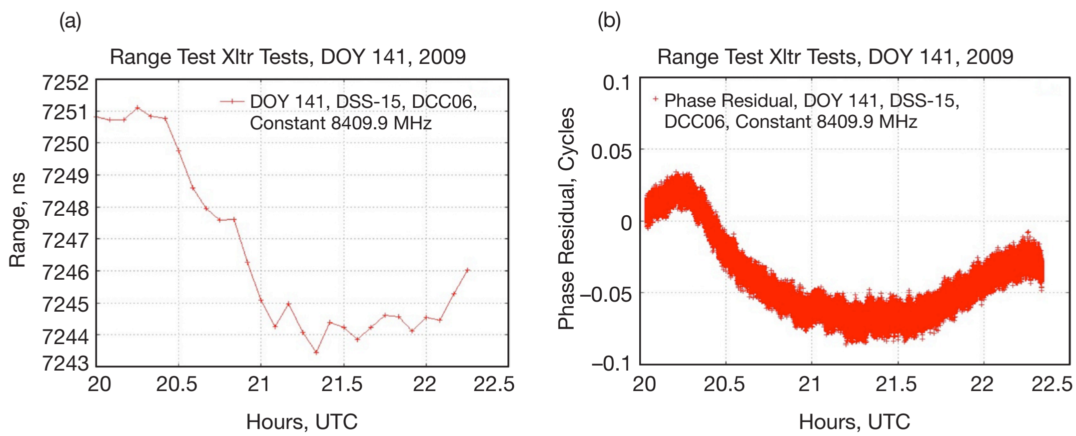


**Figure 17. DSS-15 long-loop test, May 21, 2009: (a) ranging measurement; (b) carrier phase measurement.**

These results show that range variations at non-beam-waveguide antennas are much more severe that at the beam-waveguide antennas. This is consistent with the fact that the signal at DSS-14 and DSS-15 must travel up to the feedcone rather than just to the antenna pedestal. Still, the magnitude and rate of change were surprising.

## V. Range Variations with Frequency

A concern in the beginning was variations in the measured range with frequency. Scott Bryant first noticed these in results of testing in the 238-527 laboratory with a transmit-

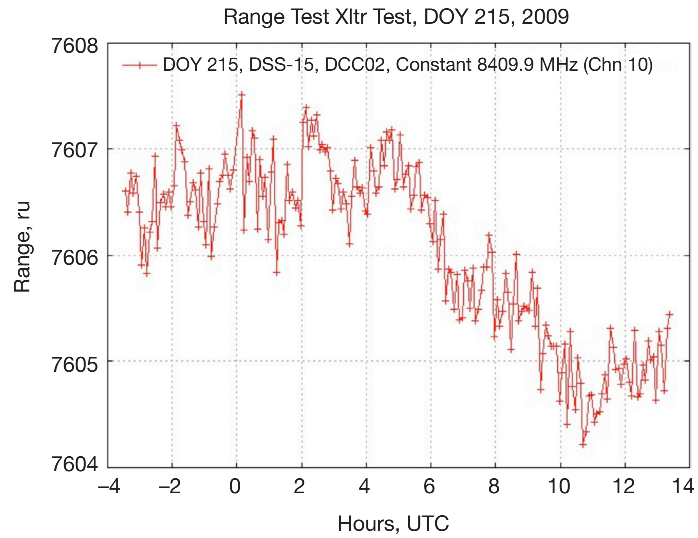


**Figure 18. DSS-15 long-loop test, June 4, 2009: ranging measurement.**

ter, long-loop, and short-loop. During the test, a range calibration (five independent range measurements, validated to be consistent within the predicted measurement error) was performed across the X-band deep space allocation at 0.5-channel steps. The sweep was repeated. The results are shown in Figure 19.

Discussions with Tim Cornish, the Transmitter Subsystem Engineer, determined that the variation was the result of voltage standing waves in the cabling and the resonance cavities in the transmitter.

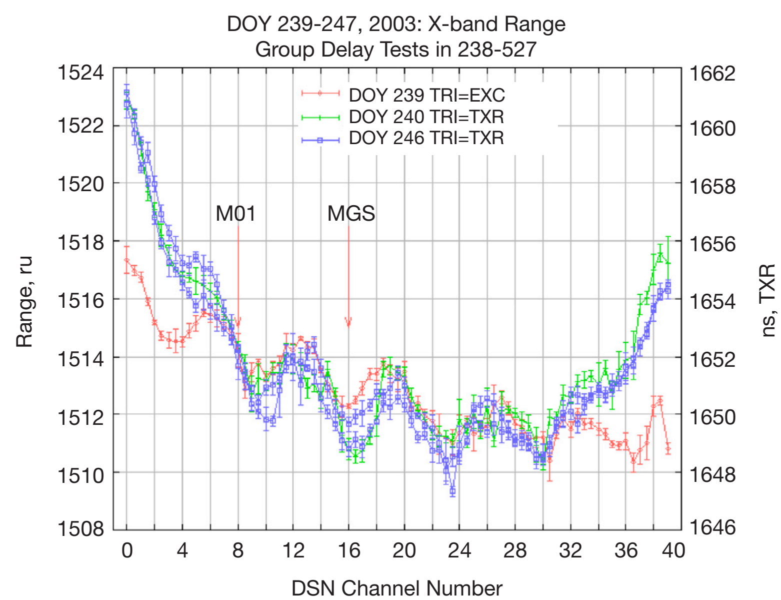


**Figure 19. X-band range group delay tests in 238-527, DOY 239–247, 2003.**

A similar test was conducted at DTF-21. Here, the X-band frequency allocation was sampled at every channel. The results are shown in Figure 20.

The DTF-21 test script was used at DSS-25 on two consecutive nights, May 13 and 14 (Figure 21). The second night the test was conducted by Bruce Klein. The two test results are consistent.

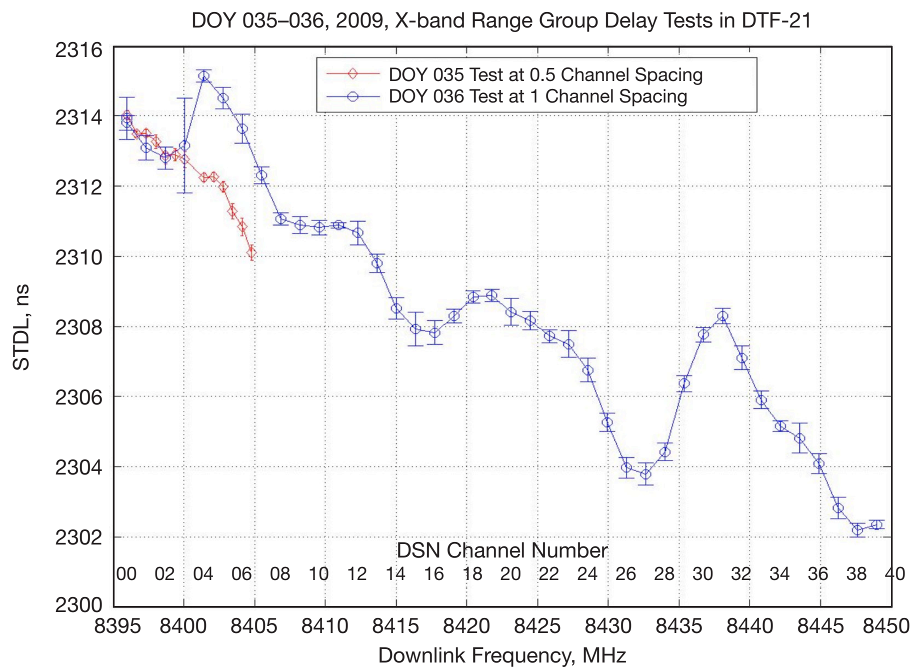


**Figure 20. X-band range group delay tests in DTF-21, DOY 035–036, 2009.**

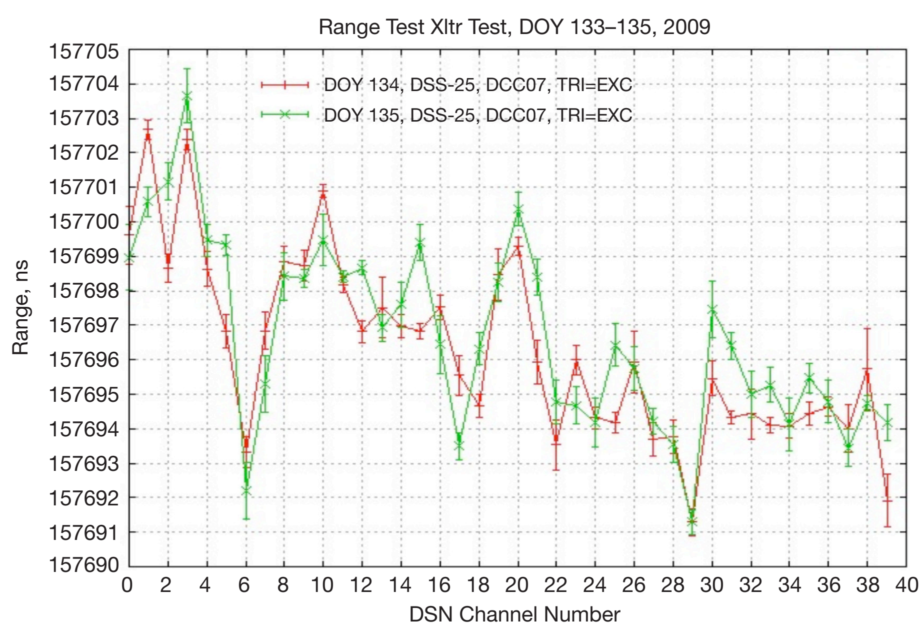


**Figure 21. DSS-25 test, May 13–14, 2009.**

Because even severe Doppler does not move the downlink over a significant part of the deep space allocation and the result seems repeatable, this was not pursued further.

## VI. Conclusions

Variations in the measured internal range were observed at all DSN tracking stations at Goldstone over a period of hours. Current DSN practice of calibrating internal range once, at precal or postcal, is inadequate to achieve 10-cm ranging accuracy even when considering just the DSN contribution. Changes at the non-beam-waveguide stations, DSS-14 and DSS-15, were by far the largest.

At DSS-25, changes of 3 ns were observed over 4 hours on consecutive days in May. Analysis of RSR data shows that the increase in the measured range was caused by the ranging modulation moving in the frequency domain with respect to the carrier, not an increase in physical delay through the tracking systems. In August, changes of over 4 ns were observed over 6 to 12 hours on 3 consecutive days. The observations in August included both "short-loop" and "loop-loop" (without and with the transmitter, respectively) and were consistent within the limits of the data collected. Several causes were investigated but the root cause remains a mystery.

Here is a summary of the conclusions from the study:

(1) Ranging calibration as currently performed in the DSN is inadequate to support 10-cm ranging.

(2) Ranging variations at DSS-25 are repeatable on a daily basis but change over months.

(3) The ranging variations at DSS-25 are not correlated to local time-of-day or equipment "warm-up."

(4) Precal range calibrations are consistent at each antenna. This is verified by the automated range calibration software, which records the measured value and compares it to measurements from previous tracks.

(5) The cause of the range variations is not obvious:

- The variations in measured range are not caused by a physical increase in the signal path, such as thermal expansion, since we see very constant carrier phase.
- The variations are not caused by either the modulation or measurement of the ranging signal since no variation shows up in DTF-21 testing using identical equipment.
- The variations are not caused by the DSN transmitter since we see identical variations, short-loop and long-loop, at DSS-25.
- The variations are not caused by modulation or demodulation onto the fiber-optic cables since these are included in the DTF-21 configuration.

- The variations are more severe at the non-beam-waveguide antennas than at the beam-waveguide antennas.

## VII. Next Step

In order to attain 10-cm ranging, the internal range delay in the DSN ranging system must be measured during tracking so that range delay variations can be calibrated. In addition, simultaneous ranging at two uplink/downlink frequencies would allow calibration of charged particle effects on delay, an important consideration for a mission to Mercury, near the Sun. An Advanced Ranging Instrument (ARI) has been proposed that meets these needs. It provides constant measurement of internal range delay and provides simultaneous range measurement at both X-/X-band and Ka-/Ka-band.


## Acknowledgments

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## References


[1] Luciano Iess, Sami Asmar, and Paolo Tortora, "MORE: An Advanced Tracking Experiment for the Exploration of Mercury with the Mission BepiColombo," *ACTA Astronautica*, vol. 65, pp. 666–675, September/October 2009.

[2] *DSN Telecommunications Link Design Handbook*, DSN No. 810-005, Module 203, "Sequential Ranging," Rev. C, Jet Propulsion Laboratory, Pasadena, California, October 31, 2009. http://eis.jpl.nasa.gov/deepspace/dsndocs/810-005/